ELECTRICAL AND ELECTRONIC MATERIALS

Code: EEC/EPM1160

Total: 4 Tutorial: 1 Lecture: 3

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Frequency dependence of dielectric constant

When a dielectric is subjected to an ac voltage, or field, the polarization of the medium under these ac conditions results in an **ac dielectric constant** that differs from the **dc value** under static conditions

Considering orientation polarization, the sinusoidally varying fields tries to line up the dipoles in one direction and then in the other direction

Frequency dependence of dielectric constant

If the instantaneous induced dipole moment <u>**μ**</u> per molecule can <u>**follow**</u> the field variation, the polarization is given as: $\mathbf{P = N \alpha \; E}$

With a very large frequency, the high mechanical time constant will prevent the system to follow up this high frequency

Frequency dependence of dielectric constant

This results in stopping all polarization mechanisms at very large frequencies and no response to a high frequency field will occur

In this case, the polarizability is zero; the dielectric constant ε_r is almost "1" for $f \Rightarrow \infty$

For low frequency the polarizability takes values from zero to its maximum value

Frequency dependence of dielectric constant

In electronic and ionic polarization

- The distance between the charges involved is changed under the applied electrical field
- A restoring force is produced
- This is similar to an **oscillator** in the mechanical systems
- The characteristic property of any such oscillating system is the phenomena of **resonance** at a specific frequency

Frequency dependence of dielectric constant

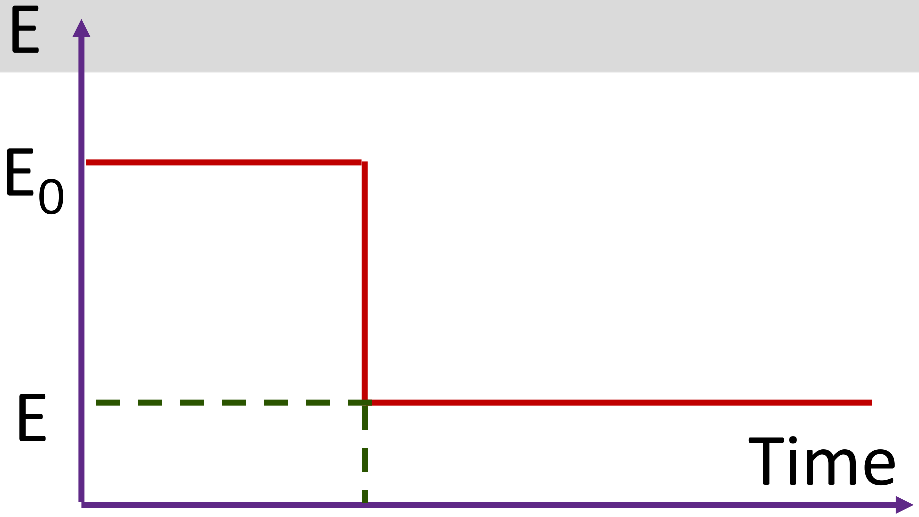
<u>In orientation polarization</u>

- there is no restoring mechanical force that pulls the dipoles back to random orientation
- The material reaches an equilibrium state with an average net dipole moment under the driving force
- If the driving force is suddenly removed, the dipoles will start to have a new equilibrium state within a specific characteristic time called **relaxation time (τ)**

It is hence enough to consider simply the two basic situations: ***<u>Dipole relaxation</u>*** and ***<u>dipole resonance</u>***

Frequency dependence of dielectric constant

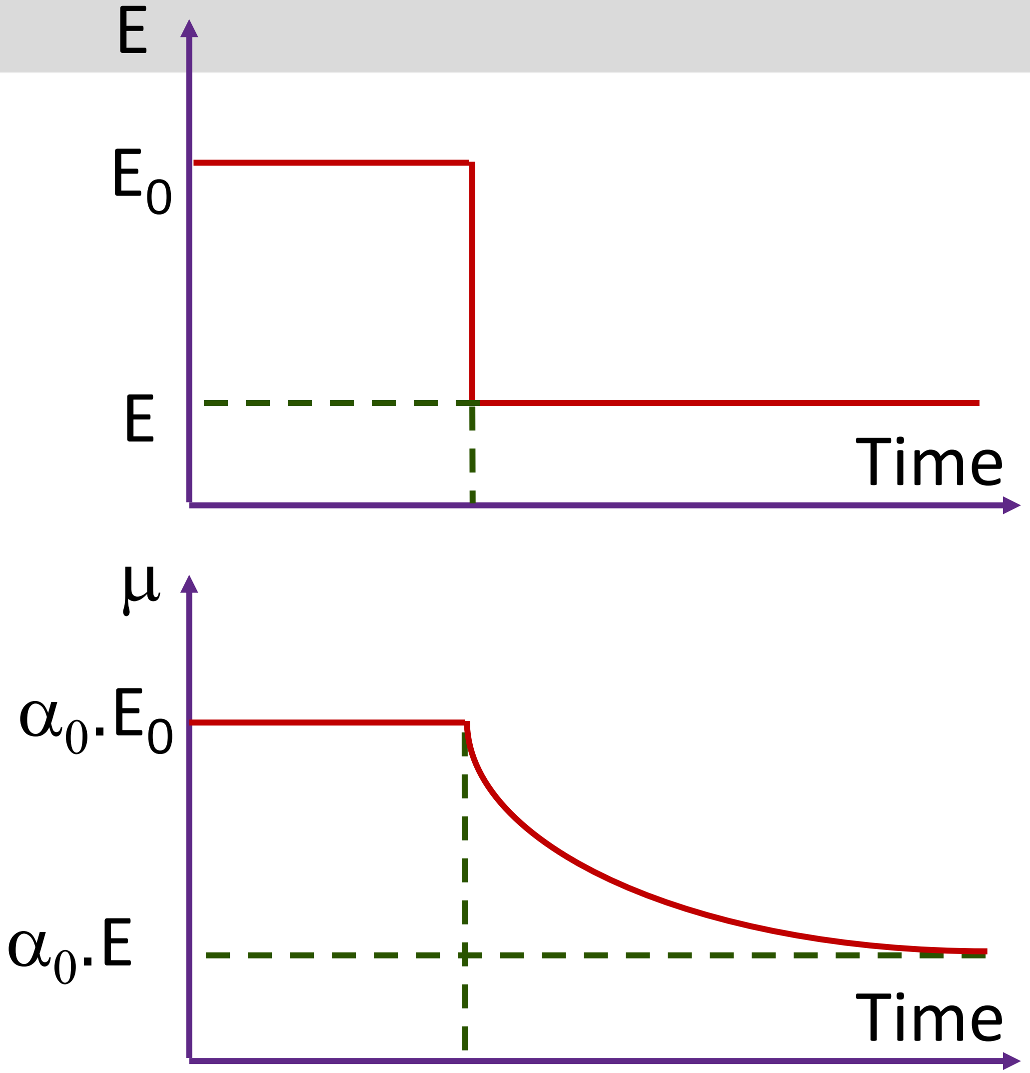
Consider the case where the field is decreased as a unit step from a value E_0 to a final value E



Frequency dependence of dielectric constant

Consider the case where the field is decreased as a unit step from a value E_0 to a final value E

The induced dc dipole moment per molecule will also decrease from $\mu_0 = \alpha_0 E_0$ to $\mu = \alpha_0 E$



Frequency dependence of dielectric constant

The rate at which the dipole moment is changing is:

$$\boxed{\frac{d\mu}{dt} = -\frac{\mu - \alpha_0 \cdot E}{\tau}}$$

For alternating field: **$E = E_0 \, . \, \exp\,(j\omega t)$**

$$\mu = \alpha(\omega).E_0.\ \exp\,(j\omega t)$$

$$\boxed{\alpha(\omega) = \frac{\alpha_0}{1 + j\omega\tau}}$$

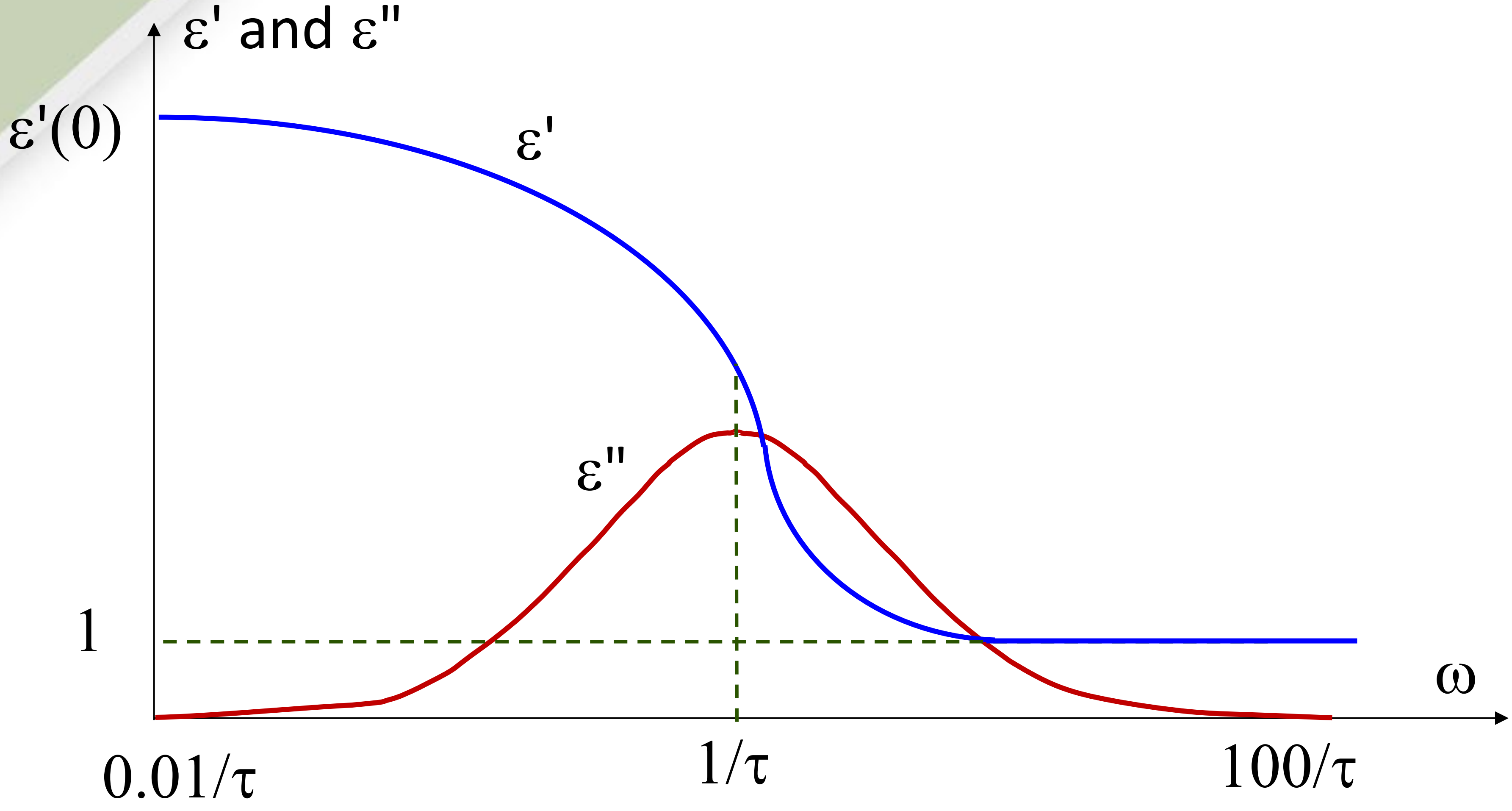
Frequency dependence of dielectric constant

$$\alpha(\omega) = \frac{\alpha_0}{1 + j\omega\tau}$$

- As a function of the frequency, the polarizability **$\alpha(\omega)$** is a complex number since **μ** and **E** are out of phase
- At low frequency, **$\alpha(\omega)$** is almost the initial value "**α_0**" and **μ** and **E** are in phase
- At normal frequency, the variation of **$\varepsilon(\omega)$** as a complex variable, i.e.

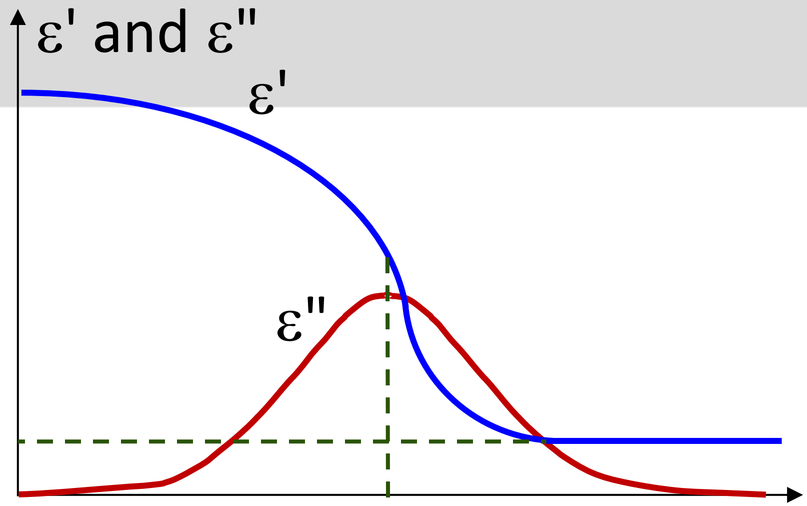
$$\varepsilon(\omega) = \varepsilon'(\omega) - j\varepsilon''(\omega)$$

Frequency dependence of dielectric constant



Frequency dependence of dielectric constant

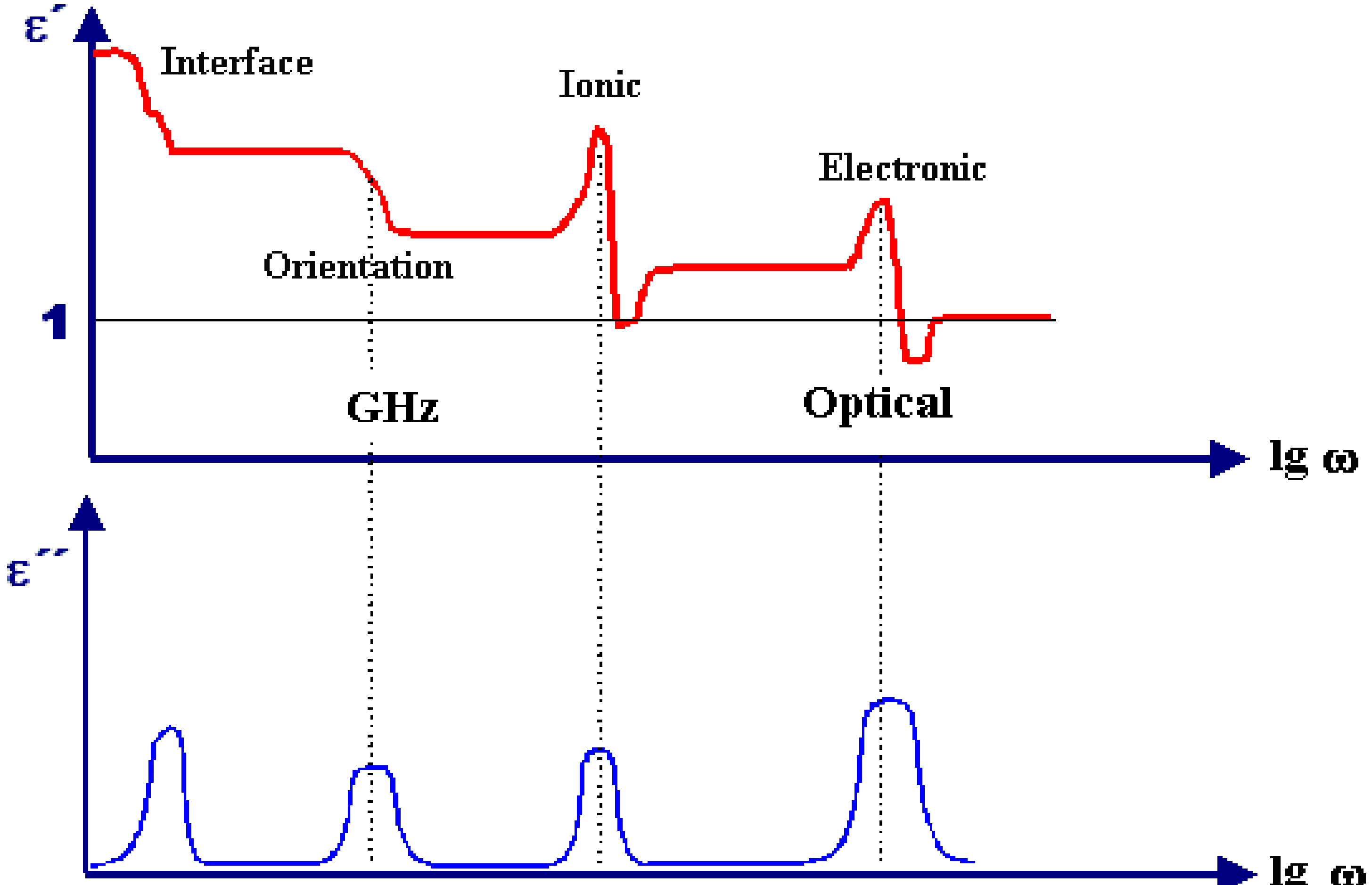
- The real part ε' decreases from its max. value ε'(0) at low frequency to unity at very high frequency



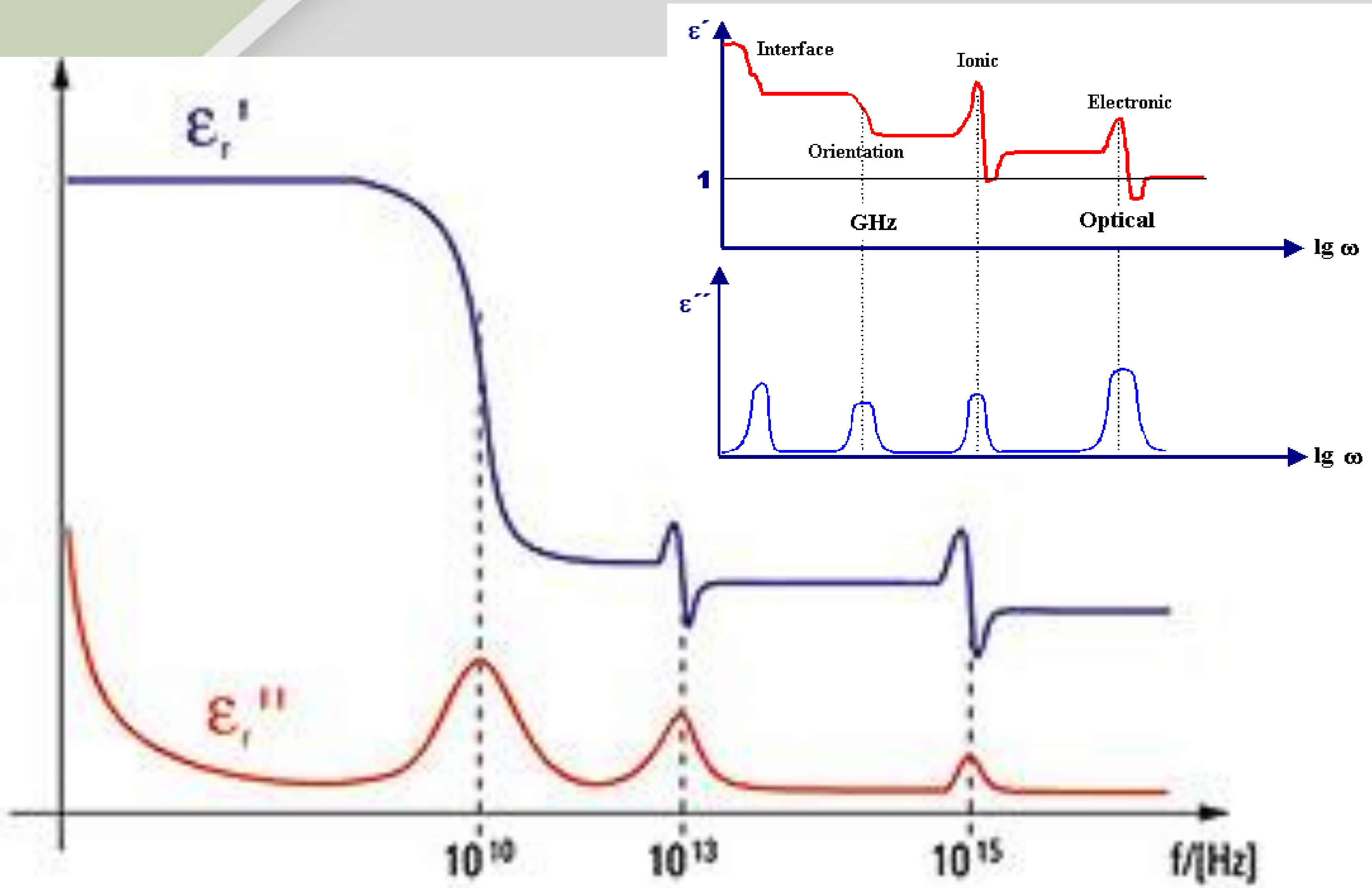
- The imaginary part ε'' has a zero value at both low and high frequencies and has a peak value at $\omega=1/\tau$
- When considering the calculation of the capacitance, the real part **ε'** is the regarded part to be considered
- The imaginary part **ε''** represents the energy lost in the dielectric as a result of the dipoles orientation against the random collisions in opposite directions

Frequency dependence of dielectric constant

The frequency dependence of the dielectric constant of a given material is a combination of all mechanisms affecting this material



Frequency dependence of dielectric constant



Dielectric Losses

The specific electric power loss L (i.e. electric power lost per unit volume) in any material in the form of heat is given by:

$$L = J \cdot E$$

where J is the current density and E is the electrical field strength

For ideal dielectrics, there is no direct current but only displacement currents $J(\omega)$ occurs for alternating voltages or electrical fields

Dielectric Losses

The displacement current is calculated as

$$\boxed{J(\omega) = \varepsilon(\omega)\ .\ j\omega\ .\ E_0\ .\ \exp(j\omega t) = \varepsilon(\omega)\ .\ j\,\omega\ .\ E(\ \omega)}$$

If the complex function $\varepsilon(\omega)$ is written in terms of its

two components: $\varepsilon(\omega) = \varepsilon'(\omega) - j \cdot \varepsilon''(\omega)$

$$\mathbf{J(\omega) = \omega \cdot \varepsilon'' \cdot E(\omega) + j \cdot \omega \cdot \varepsilon' \cdot E(\omega)}$$

Dielectric Losses

The power losses have two components: the active power that is the really lost power in the form of heat "L_A" and the reactive power that is the power extended and recovered each cycle "L_R"

$$L_A = \omega \cdot |\varepsilon''| \cdot E^2 \qquad L_R = \omega \cdot |\varepsilon'| \cdot E^2$$

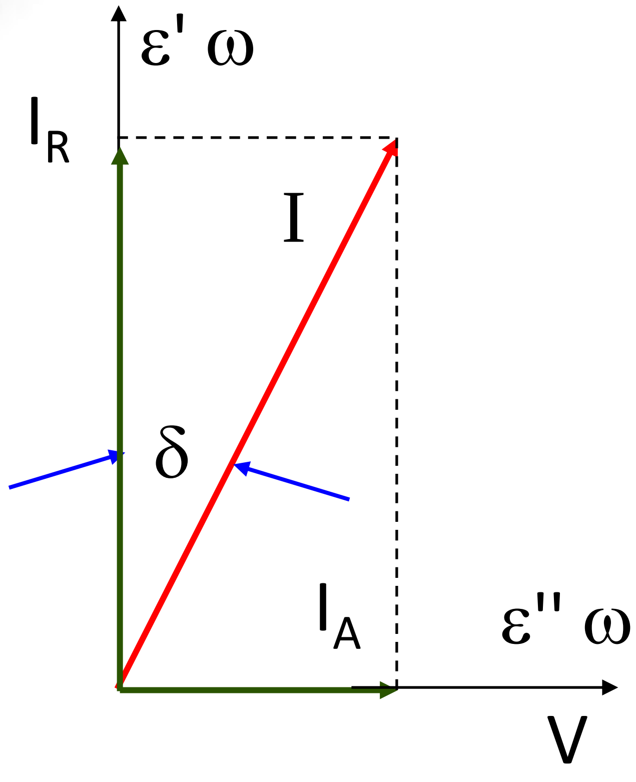
A perfect none dc-conducting material can be heated up by an ac voltage

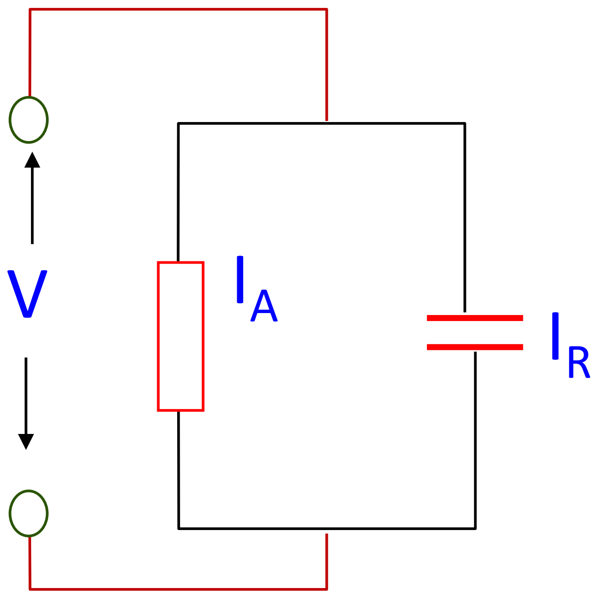
To increase the heat, frequencies around the resonance or relaxation frequency of the material are used where ε'' is maximum

Dielectric Losses

It is common to use a measure quality factor called "tangens delta" (tg δ):

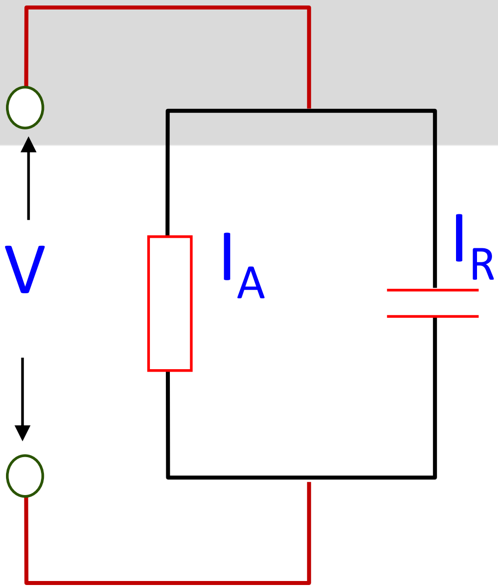
$$tg\,(\delta) = \frac{I_A}{I_R} = \frac{\varepsilon''}{\varepsilon'}$$





Dielectric Losses

The current component I_A is in phase with the applied voltage V and it corresponds to the imaginary part ε'' of the dielectric function multiplied by ω.



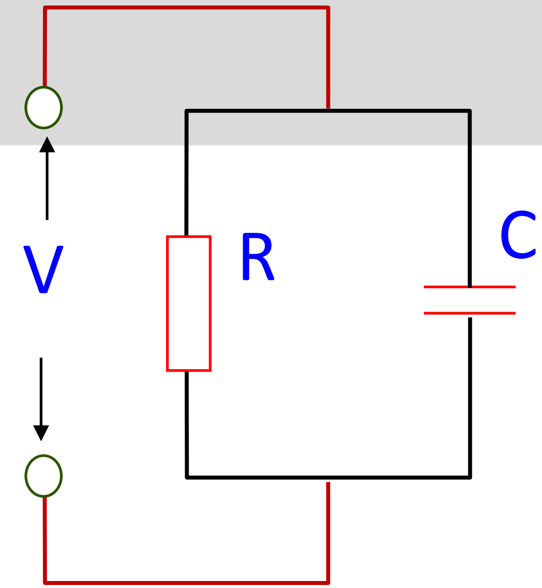
The out-of-phase current component I_R is given by the real part ε' of the dielectric function multiplied by ω

R would be infinite for an ideal dielectric

It is obvious that the smaller the angle δ or $\mathrm{tg}\ \delta$, the better with respect to power losses

Dielectric Losses

The values of the Ohmic resistor and the capacitor are frequency dependent



$$C = \frac{A \cdot \varepsilon'}{d}$$

$$R = \frac{d}{\omega \cdot A \cdot \varepsilon''}$$

The total power loss is calculated in terms of tg (δ) by substituting for ε'' by $\varepsilon' \cdot$ tg (δ)

$$L_A = \omega \cdot |\varepsilon''| \cdot E^2$$

$$tg\,(\delta) = \varepsilon'' / \varepsilon'$$

$$L_A = \omega \cdot \varepsilon' \cdot E^2 \cdot tg\,(\delta)$$

Special Dielectrics

It is not obligatory for some special materials to apply an external electrical field to get a polarization

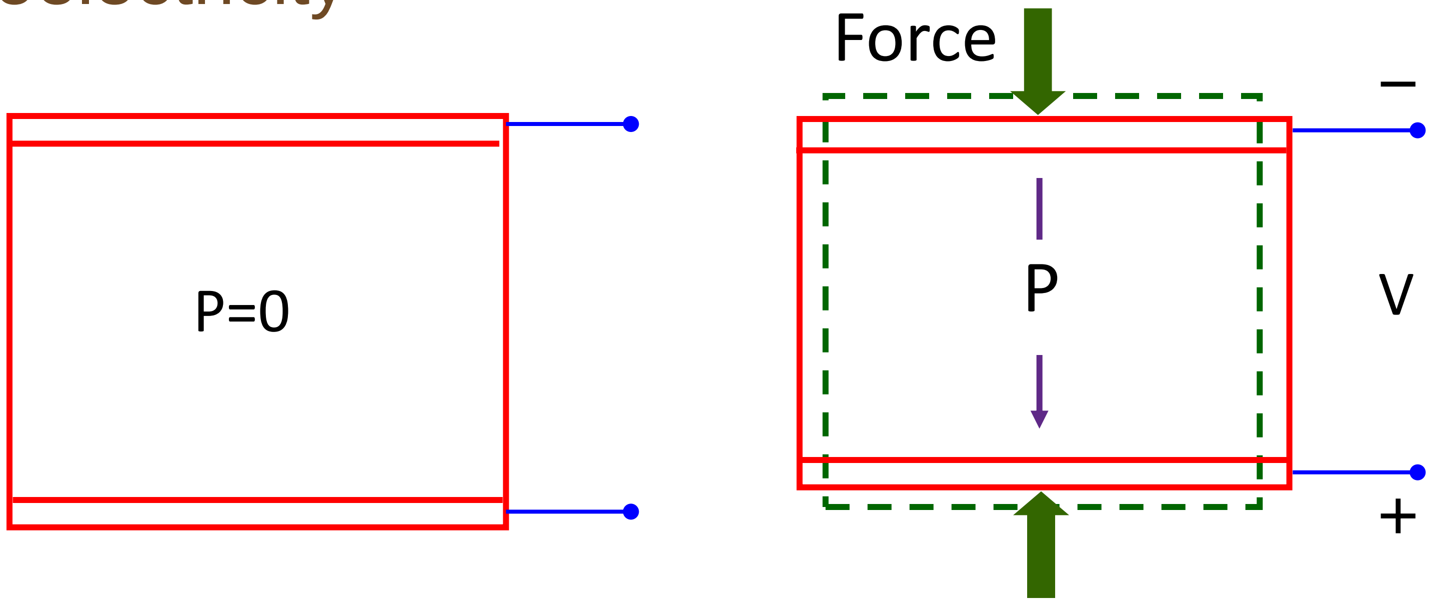
The polarization may come about by other means like the case of ***Piezoelectricity*** and ***Ferro electricity***

Piezoelectricity

When crystals with **nonuniform charge distribution** are mechanically deformed, the positive and negative charge centres are shifted by different values

The overall crystal remains electrically neutral

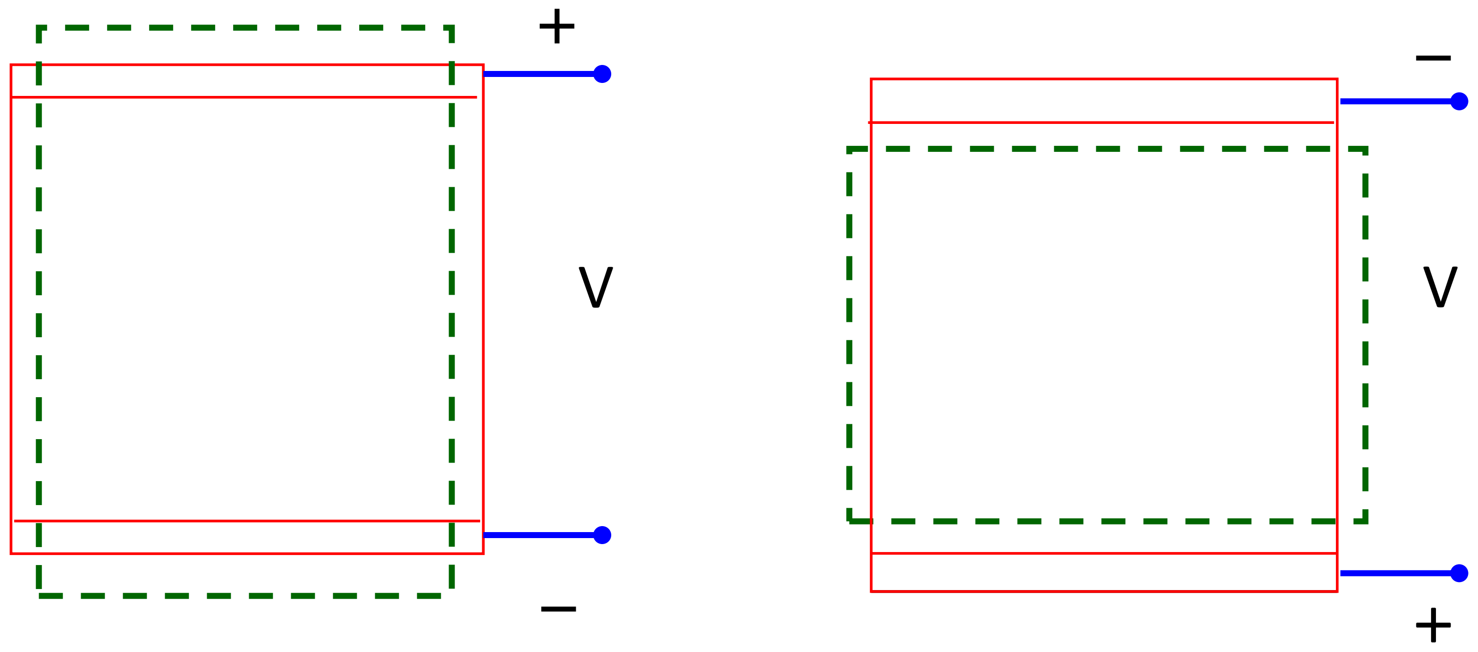
The shifting in the charge centres results in an electric polarization within the crystal known as Piezoelectricity



Piezoelectricity

The production of mechanical deformation by polarization is also possible

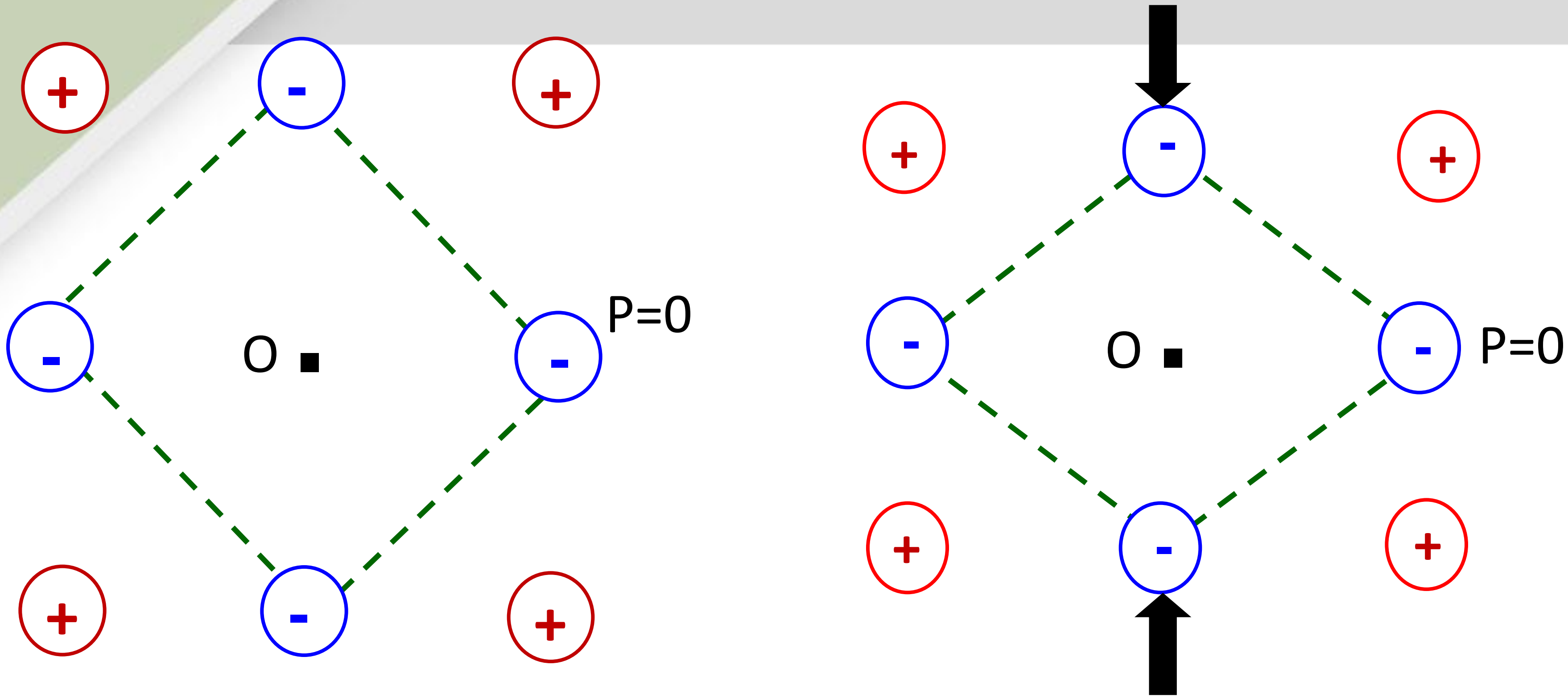
This provides a convenient **transducer** effect between mechanical and electrical oscillations



Piezoelectricity

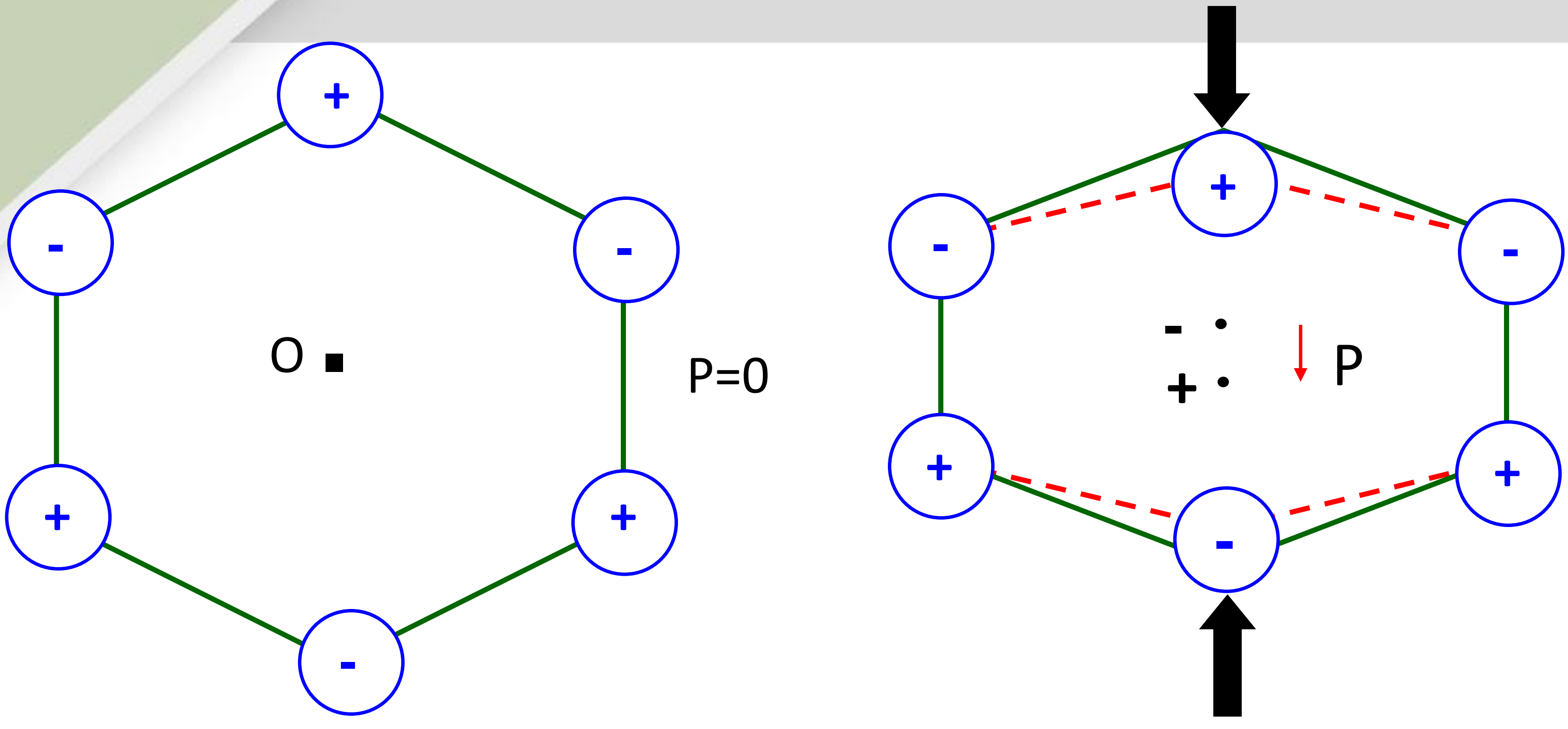
- Many crystalline materials exhibit piezoelectric behaviour
- Few materials exhibit the phenomenon strongly enough to be used in applications that take advantage of their properties
- Piezoelectricity is limited to crystals with low symmetry in single crystalline form, which requires that the crystal has no centre of symmetry

Piezoelectricity



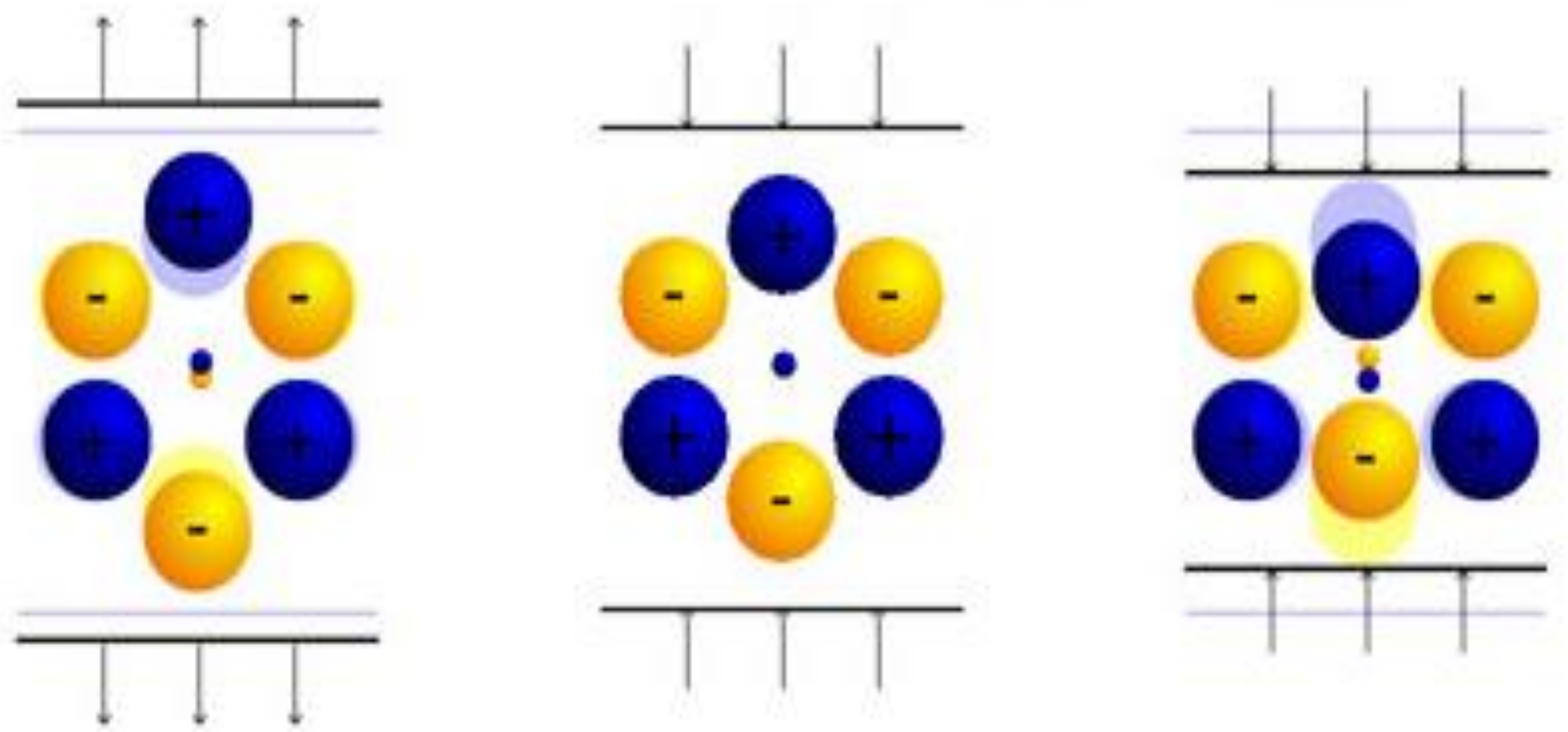
Crystal with centre symmetry

Piezoelectricity



Piezoelectric crystal without centre symmetry

Piezoelectricity



Piezoelectricity

Piezoelectricity has several major utilizations

The quartz oscillators, where suitable pieces of single crystal of quartz are given a very precisely and purely mechanically defined resonance frequency

When the piece of quartz is polarized by an electrical field of the same frequency, it will vibrate strongly, or else, it will not respond. This can be used to control frequencies at a very high level of precision

Piezoelectricity

Another application is the precisely-controlled movements

This is used normally with very small movements in the order of fractions of nm to µm

Piezoelectricity

The mechanical vibrations in quartz cause negligible losses and they have a high quality factor

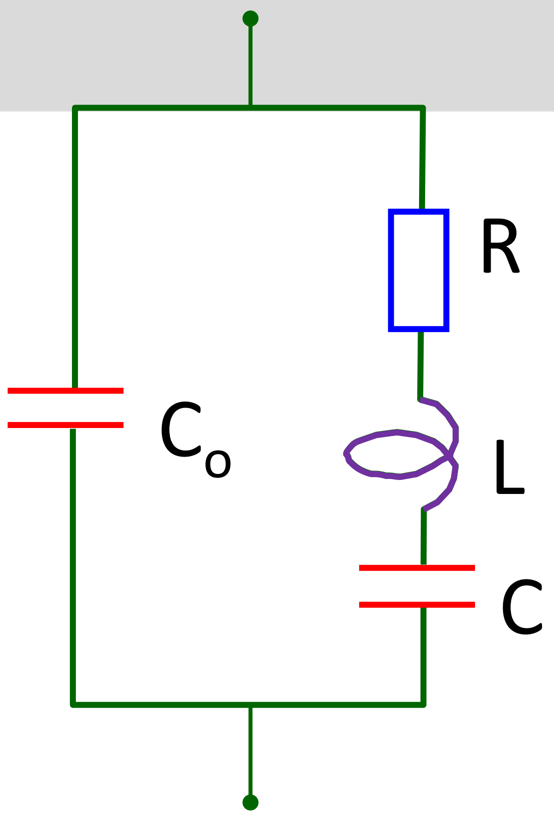
The mechanical vibrations have a nature that is in analogue to a resonant- series RLC circuit

The mechanical resonant frequency f_r is calculated as

$$\boxed{f_r = \frac{1}{2\pi\sqrt{LC}}}$$

Piezoelectricity

The parallel electrodes at opposite faces of the crystal form another capacitance that has to be modelled in parallel with the RLC circuit



There is another resonant frequency f_a due to L resonating with C and C_o in series:

$$f_a = \frac{1}{2\pi\sqrt{LC_{eq}}}$$

Where the equivalent capacitance C_{eq} is given by:

$$\frac{1}{C_{eq}} = \frac{1}{C} + \frac{1}{C_o}$$

Ferro Electricity

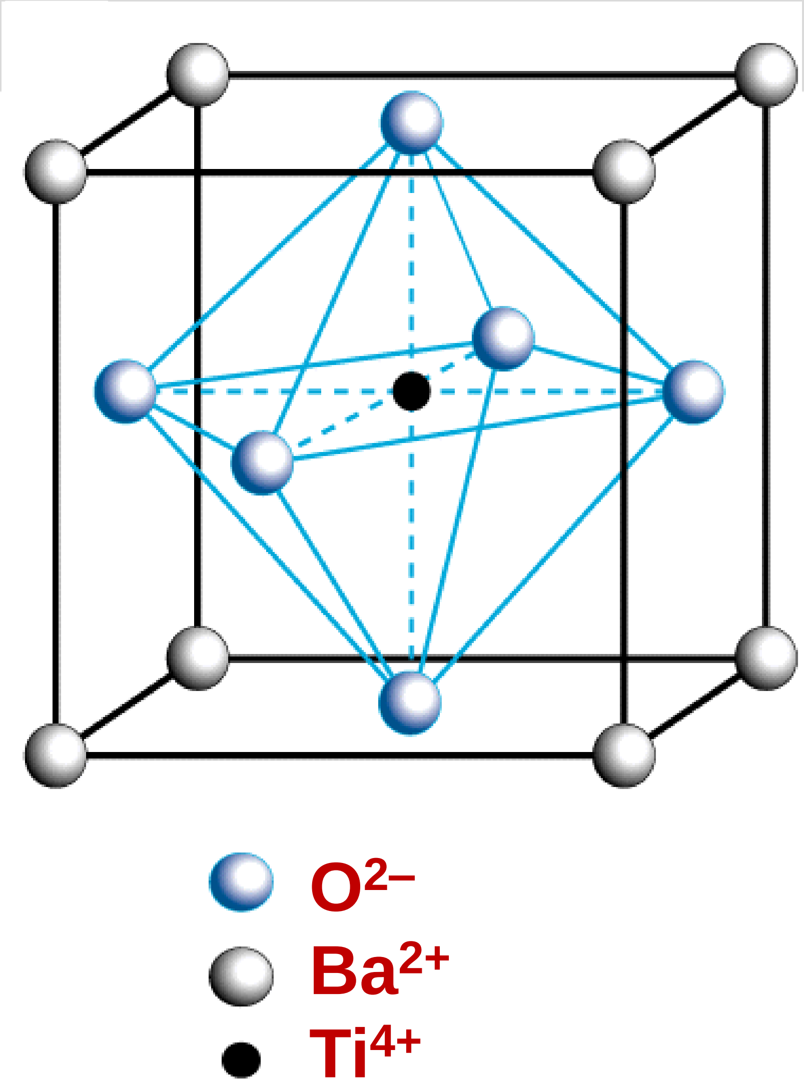
The name "Ferro Electricity" is not related to the Iron "Ferro", rather, it is correlated to the Ferro magnetism (in analogy with the ferromagnetic materials that already possess residual magnetization)

The electrical dipoles in some special materials are not randomly distributed but they interact with each other in such a way that they align themselves even without an external field

This situation results in spontaneous polarization and the material has a large value of dielectric constant

Ferro Electricity

An example of such materials that is used for many applications is the Barium titanate (**$BaTiO_3$**)
It has three different atoms with eight doubly charged **Ba^{2+}** atoms positioned on the corners of a cube, six **O^{2-}** ions on the face centres, and one **Ti^{4+}** ion in the centre of the cube

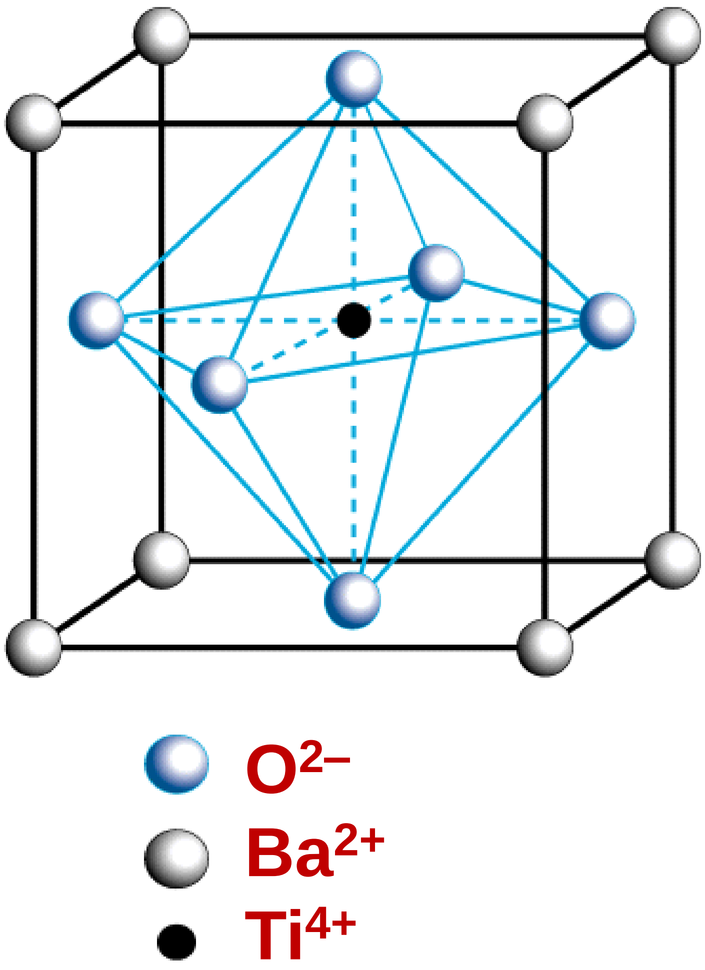


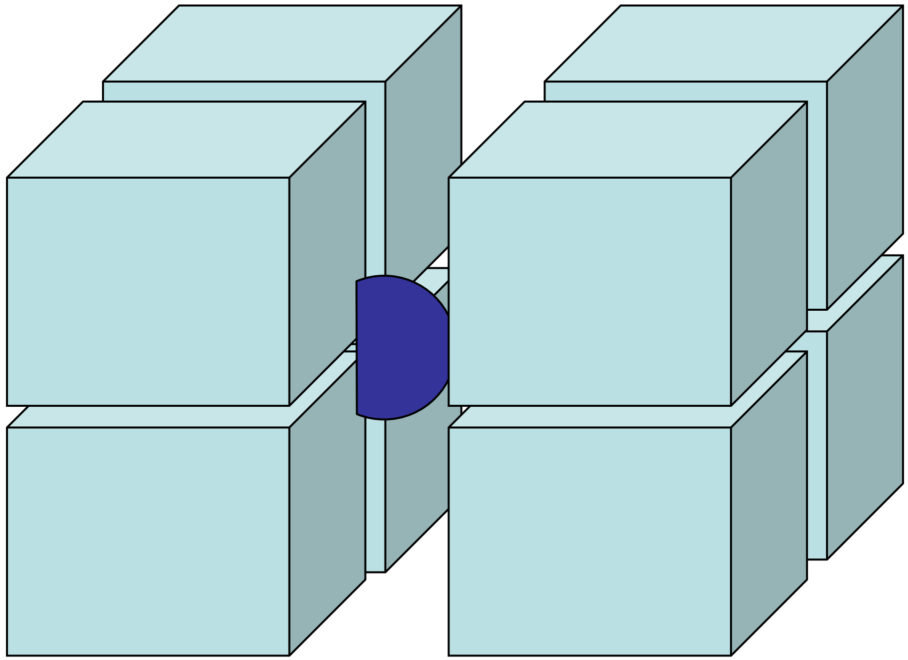
Ferro Electricity

Each one of the eight **Ba^{2+}** ions belongs to eight cells and only one equivalent **Ba^{2+}** ion belongs to this elementary cell

Similarly, each one of the six **O^{2-}** ions belongs to two cells and each cell contains three **O^{2-}** ions

On the other hand, the **Ti^{4+}** ion belongs in total to the cell. It is clear thus that the structure is **$BaTiO_3$**





Ferro Electricity

Above a certain temperature (130 ^oC) the structure has a cubic unit cell

The centre of mass is of the negative charge **O^{2-}** and the positive charges **Ba^{2+}** and **Ti^{4+}** coincide at **Ti^{4+}** ion

There exists no net polarization

If the temperature is reduced lower than 130 ^oC, the lattice forms a slightly-distorted cubic

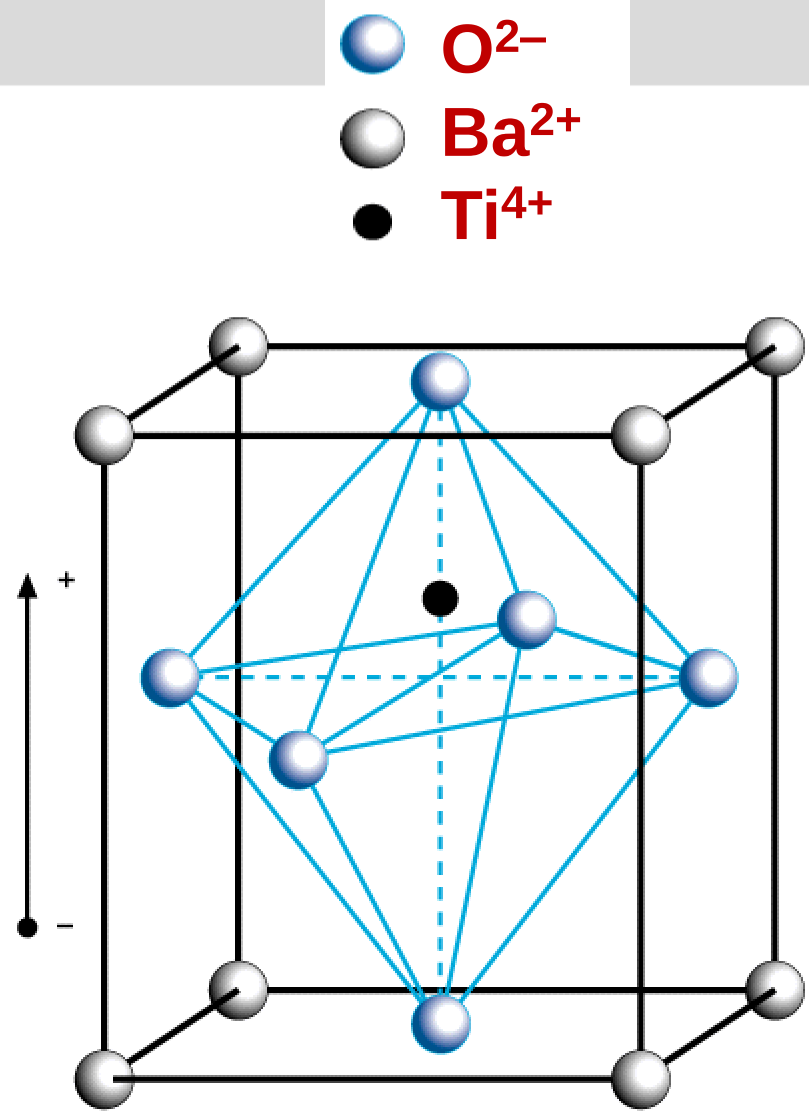
The **Ti** - ion does not sit exactly in the centre of the cube

This shift in the **Ti** – ion results in a dipole moment in each elementary cell

Ferro Electricity

The dipole moments of the neighbouring cells tend to line up

This characteristic can be useful when used with capacitors that use ferro-electric materials with high dielectric constant values



Ferro Electricity

The critical temperature, above which Ferro electricity is lost, 130 ^{o}C in this case, is called **Curie temperature**